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Feasibility of virtual surgical simulation in the head and neck region for soft tissue reconstruction using free flap: a comparison of preoperative and postoperative volume measurement

S. Yokoi[1], N. Nishio[1,2], Y. Fujimoto[1], M. Fujii[3], K. Iwami[4], Y. Hayashi[5], K. Takanari[6], M. Hiramatsu[1], T. Maruo[1], N. Mukoyama[1], H. Tsuzuki[1], A. Wada[1], Y. Kamei[6], M. Sone[1]

[1]Department of Otorhinolaryngology, Nagoya University Graduate School of Medicine, Nagoya, Aichi, Japan; [2]Department of Otolaryngology – Division of Head and Neck Surgery, Stanford University School of Medicine, Stanford, CA, USA; [3]Department of Neurosurgery, Fukushima Medical University, Fukushima, Fukushima, Japan; [4]Department of Neurosurgery, Aichi Medical University, Nagakute, Aichi, Japan; [5]Graduate School of Informatics, Nagoya University, Nagoya, Aichi, Japan; [6]Department of Plastic and Reconstructive Surgery, Nagoya University Graduate School of Medicine, Nagoya, Aichi, Japan

S. Yokoi, N. Nishio, Y. Fujimoto, M. Fujii, K. Iwami, Y. Hayashi, K. Takanari, M. Hiramatsu, T. Maruo, N. Mukoyama, H. Tsuzuki, A. Wada, Y. Kamei, M. Sone: Feasibility of virtual surgical simulation in the head and neck region for soft tissue reconstruction using free flap: a comparison of preoperative and postoperative volume measurement. Int. J. Oral Maxillofac. Surg. 2019; xxx: xxx–xxx.

Abstract. In the head and neck region, preoperative evaluation of the free flap volume is challenging. The current study validated preoperative three-dimensional (3D) virtual surgical simulation for soft tissue reconstruction by assessing flap volume and evaluated fat and muscle volume changes at follow-up in 13 head and neck cancer patients undergoing anterolateral craniofacial resection. Patients received 3D virtual surgical simulation, and the volume of the planned defects was estimated by surgical simulation. Following *en bloc* resection of the tumor, the defect in the skull base was covered using a rectus abdominis myocutaneous flap. Following surgery, computed tomography scans were acquired at day 1 and at 6 and 12 months. Virtual planned defect was on average 227 ml (range, 154–315) and was 10% smaller than the actual flap volume in patients without skin involvement of the tumor. Between day 1 and 12 months post-surgery, the volume of fat and muscle tissue in the free flap dropped by 9% and 58%, respectively. Our results indicate that 3D virtual surgical simulation provides essential information in determining the accurate volume of the required free flap for surgical defect repair and may thus help improve surgical planning and functional and esthetic outcome.

Key words: virtual surgical simulation; head and neck cancer; soft tissue reconstruction; volume measurement; anterolateral craniofacial resection.

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Tissue reconstruction using free flap transfer is a standard procedure to retain residual function and to avoid postoperative surgical complications. Particularly in the head and neck region, safe and appropriate flap transfer for surgical defects is essential in maintaining functional (swallowing, speech) and esthetic outcomes (quality of life (QOL)). Unfortunately, it is inevitable that over time, transferred flap size decreases with as much as 30%, which often results in dysphagia of lower swallowing pressure and decreased QOL due to a significant change in appearance[1–4]. However, tissue reconstruction using free flap transfer requires experience of surgical techniques and a thorough knowledge of change for fat and muscle tissue during follow-up periods, which makes it difficult for surgeons to determine the actual flap volume before surgery. Therefore, excess tissue preparation is not uncommon.

Recent technological advances have allowed more accurate imaging of the complicated anatomy of the head and neck. Despite the accuracy of imaging technologies such as computed tomography (CT), magnetic resonance imaging (MRI) and fluorodeoxyglucose positron emission tomography (FDG-PET)/CT, predicting the volume of a surgical defect prior to surgery remains challenging due to the changing resection line(s) during surgery, due to factors such as tumor location, shape and invasion to adjacent tissue.

Preoperative three-dimensional (3D) virtual surgical simulation using CT imaging has been shown to be an accessible and cost-effective method to accurately and reliably provide information during bony resections[5,6] and reconstructions involving bony structures, e.g., in orbital wall[7,8] and mandible reconstruction[9]. However, its role in soft tissue reconstruction remains to be elucidated. Here, we hypothesized that 3D virtual surgical simulation would provide useful information in soft tissue reconstruction planning in patients with head and neck cancer. The objective of this study was to utilize and evaluate the preoperative 3D virtual surgical simulation for soft tissue reconstruction by assessing flap volume and to evaluate the volume changes of fat and muscle tissue at follow-up in patients undergoing anterolateral craniofacial resection (AL-CFR).

Materials and Methods

Patients

Clinical and pathological data of 24 consecutive patients for the malignant tumors of skull base who underwent AL-CFR at our institution between 2011 and 2019 were reviewed retrospectively. The criteria for enrollment were: (1) implementation of preoperative virtual surgical simulation; (2) presence of follow-up CT scans at day 1, and at 6 ± 2, and 12 ± 2 months postoperatively; and (3) no tumor recurrence within 12 months. Eleven patients were excluded from this study due to the tumor recurrence within 1 year after the surgery or absence of follow-up CT scans. This study was approved by the ethics review committee of Nagoya University Hospital (2018-0398) and was performed in accordance with the Helsinki Declaration of 1975 and its amendments. Written informed consent was obtained from all patients.

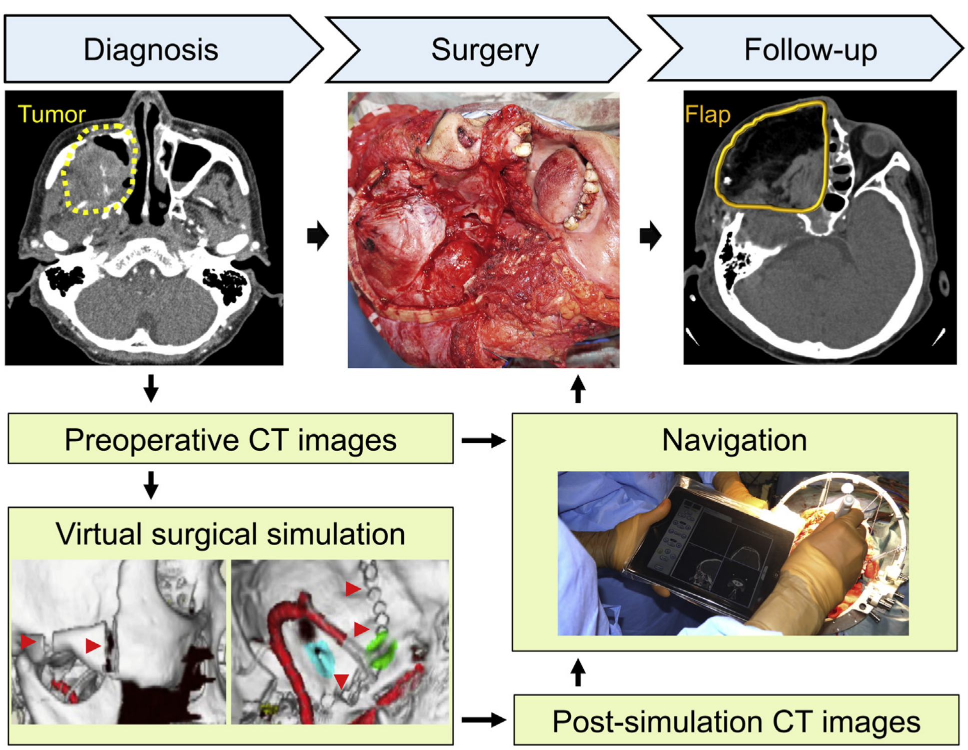

Fig. 1. Surgical workflow using preoperative virtual surgical simulation. Before surgery, a preoperative computed tomography (CT) scan was obtained and transferred to the virtual surgical simulation system. In the virtual surgical simulation, essential anatomy (tumor, carotid artery, cavernous sinus) was easily identified with different colors and a bony resection line was made in post-simulation CT. During surgery, surgeons could refer to all data from virtual surgical simulation using navigation system. After surgery, the patients received a follow-up CT scan.

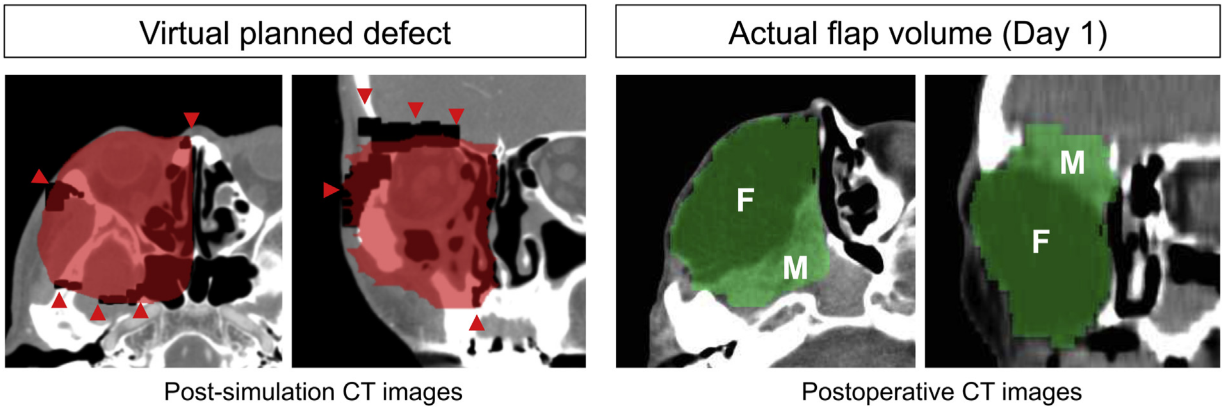

Fig. 2. Volume measurement of preoperative virtual planned flap and actual flap. Using post-simulation computed tomography (CT) images or follow-up CT images, the volume of the planned defect and actual flap was measured. F, fat tissue; M, muscle tissue.

Treatment Strategy

Patients underwent AL-CFR with orbital exenteration in an *en bloc* fashion as described previously[10,11]. Briefly, using a Weber–Fergusson incision, the tumor was removed in an *en bloc* fashion including surrounding tissues such as the orbit, hard palate, oral mucosa, and affected mucosa of the nasal septum. A frontotemporal craniotomy was performed, and the anterior and middle cranial bases were exposed epidurally. After *en bloc* resection of the tumor, the defect in the cranial base was covered using a rectus abdominis myocutaneous (RAM) flap. Orbital bony reconstruction with free flap was not performed because the orbital content was removed with the tumor. In the case where the eyelid was preserved, the eye socket was made secondary for later use of an artificial eye. During surgery, a Vector Vision Compact Navigation System (BrainLAB, Munich, Germany) was used to determine the positional relationship between the tumor and surrounding normal tissue[12]. Tumor margins were evaluated in all cases, and postoperative radiotherapy (50–60 Gy in 2-Gy fractions at five fractions per week to the tumor bed) was administered within 8 weeks of tumor resection.

Routine postoperative CT scans were obtained at the day after surgery (Day 1) with intubation in the Intensive Care Unit to check the condition of the intracranial lesion, and follow-up CT scans were acquired at 6 and 12 months postoperatively to monitor the recurrence of the tumor as per standard of care.

Three-Dimensional Virtual Surgical Simulation

The surgical workflow for preoperative 3D virtual surgical simulation is shown in Fig. 1. Preoperative CT scans (top of head to mandible, 0.5–1.0 mm slice thickness; 64-row multidetector Aquilion scanner; Toshiba, Tokyo, Japan) were obtained within 2 weeks of the planned surgery and were used for the surgical simulation and the intraoperative navigation system. 3D virtual surgical simulation was performed using the Virtual Surgiscope, which uses a volume rendering method to generate the 3D virtual environment from the acquired CT images[10]. Key anatomic structures (i.e. internal carotid artery or cavernous sinus) were rendered in different colors by extracting these regions from the CT images in advance. In this 3D virtual surgical simulation, the line of resection was determined after which a simulated osteotomy was performed using the virtual resection function. Repeated virtual resections are possible in the system such that the optimal line of resection be predicted.

Volume Measurements of the Virtual Planned Defect and the Actual Flap

Volume measurements of the virtual planned defect and the actual flap were performed using post-simulation CT images and follow-up CT images as shown in Fig. 2. To measure the volume of the virtual planned defect all post-simulation CT images were transferred to the original software ‘PLUTO’, which was developed at our institution[13,14]. Subsequently, all thin-section images of follow-up CT scans (day 1, 6 and 12 months) were transferred to Synapse Vincent volume analyzer (Fujifilm Medical Co., Ltd., Tokyo, Japan) to measure the volume of the actual flap as described previously[15]. The borders of the planned defect or reconstructed free flap were traced manually on a screen using a mouse-controlled cursor on an axial image, and subsequently the volume of the virtual planned defect and the actual flap was calculated. The radiodensity of actual free flap was measured in Hounsfield units (HU) for the follow-up CT scans to discriminate fat and muscle tissue. The HU scale is a quantitative measure of radiodensity that ranges from -1000 for air to +1000 for bone and mean HU, range, and standard deviation (SD) were calculated for all CT images. Additionally, we separately measured the fat volume and HUs of the reconstructed flap. Muscle volume was determined follows: total flap volume - fat volume = muscle volume. All measurements were performed by two head and neck surgeons, independently, and the mean values were used for analysis.

Statistical Analysis

Descriptive statistics and figures were obtained using GraphPad Prism (Version 6.0c, GraphPad Software, La Jolla, CA, USA). Results are expressed as the mean with range. To evaluate whether there is a correlation between flap volume changes in follow-up and postoperative radiotherapy, a Mann–Whitney *U*-test was performed by comparing patients that did not or did receive radiotherapy. The reproducibility of the two observers was evaluated using intraclass correlation coefficients (ICCs) using IBM SPSS Statistics for Windows, version 24 (IBM Corp., Armonk, NY, USA).

Results

Patients

Thirteen patients were included in the study (10 men, three women) with a mean age at the time of surgery of 65 years

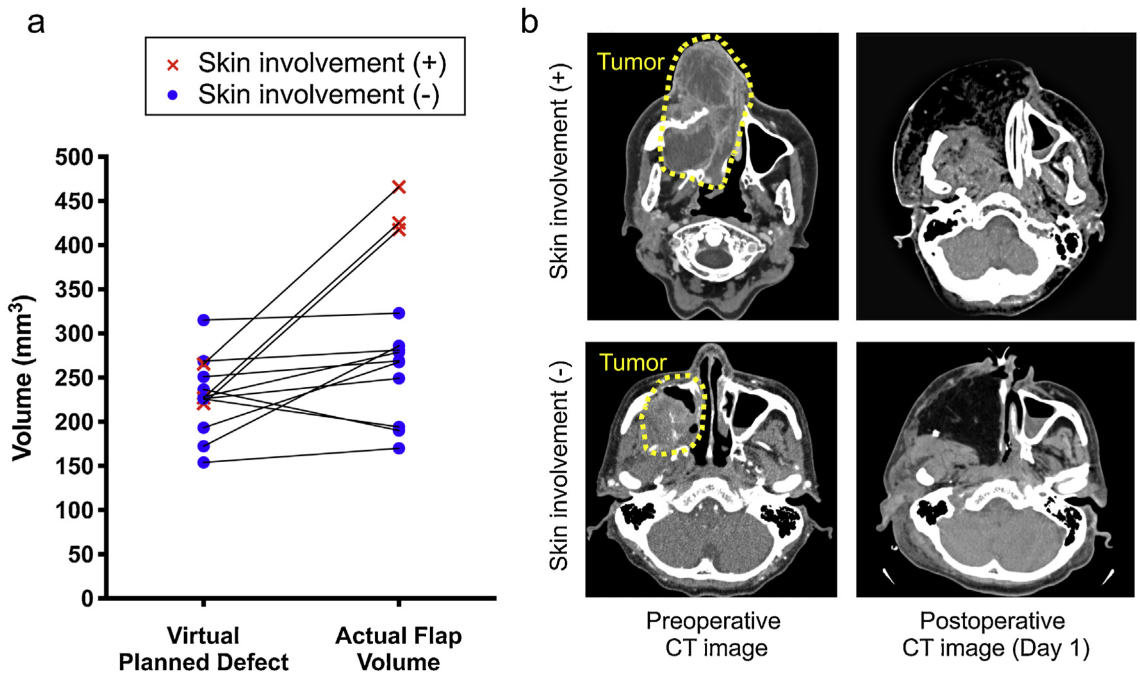

Fig. 3. (A) Comparison of preoperative virtual planned defect and actual free flap volume after surgery in 13 patients undergoing anterolateral craniofacial resection. (B) Representative pre- and postoperative computed tomography (CT) images in patients with/without skin involvement of the tumor.

(range, 53–76) and a mean body mass index (BMI) of 20.3 kg/m^2 (range, 16.3–24.5). The primary tumor resided in the maxillary sinus in eight patients, ethmoid sinus in two patients, cheek skin in two patients and orbit in one patient. All patients were clinically staged T4a ($n = 11$) or T4b ($n = 2$). In follow-up, in six patients postoperative complications occurred. In three patients, local infection(s) were reported due to plate implantation. In two of these three patients, we proceeded with plate removal and debridement. Partial necrosis developed in two patients. One patient suffered from brain hemorrhage without any subsequent complications. Nine patients received 50–60 Gy radiotherapy as an additional postoperative treatment.

Preoperative Virtual Planned Defect vs Actual Flap Volume

The results of volumetric analysis between the virtual planned defect and actual flap are shown in Fig. 3A. Extended skin resection was needed in three patients due to skin involvement of the tumor. In the nine patients without skin involvement of the tumor, the mean volume of the preoperative virtual planned defect was 227 ml (range, 154–315) and that of actual flap was 251 ml (range, 170–323), which indicated the virtual planned defect was 10% smaller than the actual flap size at day 1 postoperatively. In the three patients with skin involvement of the tumor, the mean volume of the preoperative virtual planned defect was 237 ml (range, 221–266) and that of actual flap was 436 ml (range, 418–466), which indicated the virtual planned defect was 46% smaller than the actual flap size at day 1 postoperatively. Fig. 3B shows two representative cases in patients with or without skin involvement of the primary tumor.

The reproducibility of the two observers was high; the ICC was 0.986 (95% confidence interval (CI): 0.798–0.998), indicating satisfactory stability of our process of the volumetric analysis.

Changes in Fat and Muscle Volume in Actual Flap

Fig. 4 shows the changes of the actual flap volume in follow-up. The mean actual flap volume was 294 ml (range, 170–466) at day 1 postoperatively, 194 ml (range, 92–279) at 6 months, and 207 ml (range, 98–361) at 12 months follow-up, which resulted in 34% decrease at 6 months and 29% decrease at 12 months, respectively. No correlation was found between postoperative radiotherapy and total flap volume change from day 1 to 6 months and to 12 months after surgery ($P = 0.41$).

The mean fat volume in the actual flap was 171 ml (range, 70–334), 131 ml (range, 40–228), and 157 ml (range, 62–319) at day 1, 6, and 12 months follow-up, respectively. This translated into a 24% decrease at 6 months and 9% decrease at 12 months. The mean radiodensity of fat in the actual flap was -86 HU (range, -107 to -41).

The mean muscle volume in the actual flap was 122 mL (range, 81–169) at day 1 postoperatively, 63 ml (range, 31–113) at 6 months, and 51 ml (range, 31–76) at 12 months, which resulted in 48% decrease at 6 months and 58% decrease at 12 months, respectively.

Discussion

Preoperative volume measurement for free flap reconstruction is a promising technique and has been reported to be highly accurate for breast reconstruction procedures[16,17], but not for soft tissue reconstruction in the head and neck region due to the complicated surgical anatomy and difficulty of prediction of tumor resection line(s). In the current study, using 3D virtual surgical simulation, we compared the planned defect volume with the actual flap volume after tumor resection in patients with head and neck cancer undergoing AL-CFR. Our study demonstrated that the virtual planned defect was on

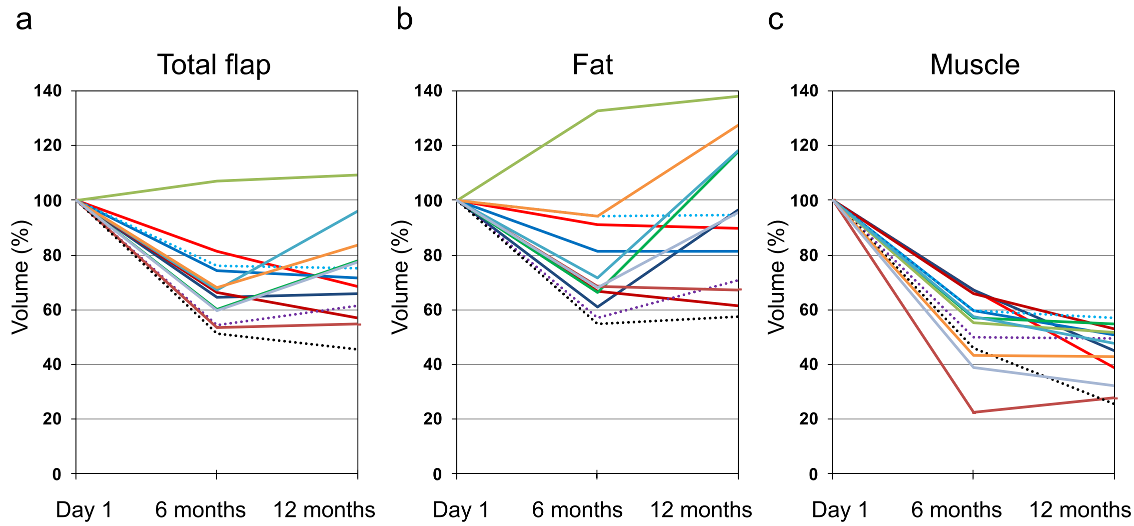

Fig. 4. Changes of volume in reconstructed free flap (total/muscle/fat) during the follow-up period in 13 patients undergoing anterolateral craniofacial resection. Changes in total, fat and muscle volume in actual flap were separately measured using follow-up CT images at day 1, 6 months and 12 months after surgery. (A) Total flap volume, (B) fat volume, (C) muscle volume.

average 227 ml and was 10% smaller than the actual flap volume in patients without skin involvement of the tumor, indicating the feasibility of virtual surgical simulation for soft tissue reconstruction when planning the free flap preoperatively. Interestingly, in the cases with skin involvement of the tumor, the volume of the actual flap was much larger than that of planned defect (237 ml vs 436 ml). This was because, in the cases with skin involvement, the reconstruction was performed to prepare adequate amounts of tissue for the secondary reconstruction of important landmarks of the face; such as external nose, lip, or eyelids. Our preoperative volume measurement for soft tissue reconstruction could be applied not only in patients with AL-CFR, as demonstrated in thus study, but also shows promise for patients with other types of head and neck cancers that typically underdo *en bloc* resection, such as total/hemi glossectomy or total/partial maxillectomy.

Virtual surgical simulation is becoming more common in clinical oncologic fields, with the main goal being to improve cosmetic and functional outcome and to achieve complete resection with tumor-free margins. However, intraoperative use of the technology is via the accuracy of the virtual simulated planned resection compared with the actual resection. To correct for this, we loaded the post-simulation CT images with planned osteotomy (i.e. virtual resection) into the navigation systems and co-registered these with the preoperative CT images. As such, with an error margin of approximately 4 mm[10], the pointer tip of the navigation device could be directed to, e.g., the deep region during surgery; the screen of this system displays the corresponding positions on axial, coronal, and sagittal images, and the precise position is confirmed immediately. Hence, the actual resection line could be compared to the virtual osteotomy in real-time to help the surgeon to achieve the ideal resection line.

Based on the deficiency of the skull base region, the flap size and shape were determined during surgery. We previously reported on actual flap design and technique for AL-CFR in order to cover the skull base region and to improve the cosmetic and functional aspects of the patient after surgery[11]. Of note, we often encounter tumor invasion to surrounding tissues during surgery, resulting in the need to change the flap size and shape corresponding to the organ deficiency. In our study, this resulted in large volume differences between the virtual planned defect and actual flap. Although the resection line was affected by tumor invasion to surrounding tissues, performing the volume measurement of virtual surgical simulation allowed the surgeons to predict the required free flap volume preoperatively and to avoid the excess tissue preparation for tissue reconstruction.

Quantitative CT assessment of the long-term outcomes of free flap reconstruction in this study indicated that the average absorption rate of the transferred free flap was 34% and 29% when assessed 6 and 12 months after surgery, respectively, which is consistent with previous literature reporting on free flap absorption rates of up to 30% at 12 months after surgery in the head and neck region[1–4]. Furthermore, we separately measured the absorption rates of the fat part and muscle part in the transferred free flap. It is well known that the muscle volume in reconstructive surgery loses volume over time because of denervation and disuse atrophy. Yamaguchi et al.[2] reported that average decrease rate in muscle tissue was 50% at an average of 12 months after surgery in 17 patients underwent free flap reconstruction with RAM flaps or anterolateral thigh flaps. Similarly, Han et al.[18] demonstrated that the rectus abdominis muscle of the transverse RAM flap in breast reconstruction lost more than 70% of its volume in the first 15 months. Our results of muscle decrease rate of 58% at 12 months after surgery are in line with these reports. Whether postoperative radiotherapy should be considered a risk factor for free flap volume decrease remains controversial[1,4,19–21]. Our study demonstrated that postoperative radiotherapy did not affect postoperative flap volume loss with no differences in flap volume changes found between patients that did and did not receive postoperative radiotherapy. Further studies with larger patient cohorts are necessary to resolve radiotherapy effect for flap volume.

It is well known that the HU value for fat tissue ranges from -10 to -190 in CT images[22,23]. Using HU values allowed us to discriminate the fat tissue from the entire transferred flap and allowed us to evaluate the fat tissue and the other regions (mainly, muscle tissue) separately. In this study the HU of the fat tissues calculated from CT images during follow-up periods ranged from -107 to -41 HU (mean value, -86 HU) and was consistent with previous studies, which suggested the volume measurement using CT imaging was appropriate for soft tissue reconstruction with HU values. Taken together, the prolonged effect of the decreased fat and muscle tissue volume in functional and esthetic outcome should be considered and anticipated for when planning soft tissue reconstruction using free flap transfer and determining the ratio of fat and muscle tissue.

This study has several limitations. This was a retrospective study performed at a single institution with a small number of patients. Because we measured the transferred flap volume using a CT imaged-based method on day 1 post-surgery, we are not able to correct postoperative volume changes caused by, e.g., tissue edema and swelling. To improve the accuracy of flap volume estimation, and intraoperative water displacement measurement based on Archimedes' principle may be a useful method for shaping free tissue transfers, especially in irregularly shaped objects[24]. Hence, our results should be validated by prospective volume measurement study including intraoperative water displacement measurement with a larger number of subjects. Furthermore, we assessed the flap volume at 12 months after surgery, but it may also be necessary to observe long-term beyond 1 year to assess whether further deformation occurs.

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Competing interests

None.

Ethical approval

This study was approved by the Nagoya University Clinical Research Review Board (registration number: 2018-0398). All procedures were executed strictly following the tenets of the Declaration of Helsinki.

Patient consent

We used a clinical photograph in Fig. 1, and written informed consent was obtained from this patient.

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Address:
Naoki Nishio
Department of Otorhinolaryngology
Nagoya University Graduate School of Medicine
65 Tsurumai-cho
Showa-ku
Nagoya
Aichi
466-8550
Japan
Tel.: +81 52 744 2323
fax: +81 52 744 2325
E-mail: naokin@med.nagoya-u.ac.jp